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Sensitivity of the Long-term Observation-error Survey Series (LOSS) model to variable stock-recruit steepness and stock depletion inputs: A test case using Gulf of Maine haddock

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Introduction

The GARM 2008 Models Meeting Panel recommended that for stocks currently using the Relative Trend class of models (e.g., AIM) “alternative models should be explored that both have a stronger basis in biology and more explicitly address uncertainty” (O’Boyle, 2008). Specifically, age-structured models were recommended that incorporate life history parameters and which allowed direct estimates of biological reference points; e.g., age-structured production model (ASPM) (Payne et al. 2005, Brandão and Butterworth 2008).

Since 2002 biological reference points for the Gulf of Maine haddock stock have been calculated using An Index Method, AIM[1] (NEFSC 2002). This model is assumed to be informative given the strong relationship between the relative fishing mortality and replacement yield for this resource. Because of this strong relationship, the Gulf of Maine haddock stock is good candidate to assess the performance of age-structured production models on northeast United States groundfish stocks. This paper explores the application of a specific age-structured production model, the Long-term Observation-error Survey Series (LOSS) model, using Gulf of Maine haddock. Additionally the sensitivity of the model is explored relative to the input variables, stock-recruit steepness and stock depletion.

Methods

The LOSS model is similar to the age-structured production model (ASPM) used by Payne et al. (2005) and Brandão and Butterworth (2008) among others. The model specifications are outlined in Appendix A. In addition to catch and an observed index of abundance the model requires five input vectors: natural mortality (M), weight-at-age (WAA), maturity-at-age (MAA), a single fleet selectivity and an index selectivity. These vectors are held constant for all years in the LOSS model.

Total annual catches of Gulf of Maine haddock from 1963 to 2006 included commercial landings, commercial discards and recreational landings. The observed index values were derived from the NEFSC autumn bottom trawl survey biomass (kg/tow) indices with door and vessel conversion factors applied (Table 1). Natural mortality was assumed constant at 0.2. Average weight-at-age was calculated using von Bertalanffy growth curve (W_{inf} = 3.6516m k = 0.1061, W_0 = 0.001) fit to NEFSC autumn bottom trawl survey data collected from 1992 to 2007. Maturity-at-age were derived by fitting a logistic model (O’Brien et al. 1993) to female maturity observations from NEFSC spring bottom trawl survey data collected from 1977 to 2007. Fleet and index selectivity patterns were assumed to be flat-topped (Table 2).

[1] *NOAA Fisheries Toolbox Version 2.10, 2006. An Index Method (AIM), Version 1.4.1. [Internet address: http://nft.nefsc.noaa.gov].*

The model was run over a wide range of stock-recruit steepness (0.25 to 0.95 in 0.10 intervals) and depletion values (0.1 to 1.0 in 0.1 intervals) for a total of 80 runs.

Results

There was a clear minimum objective function over the range of steepness and depletion values (Fig. 1a), which occurred with a steepness value of 0.65 and depletion value of 0.8 (run 61, Table 3). Despite a clear minimum value of the objective function, none of the runs are statistically different from one another with values of the objective function ranging from 21.795 to 22.517. However, there are large differences in the implications for stock status determination (Fig. 1b and c).

The reference model run (run 61, obj. func. = 21.795) estimates F_{2006}/F_{msy} at 0.744 and SSB_{206}/SSB_{msy} at 0.600; a stock status determination of not overfished, but overfishing is not occurring. This is in conflict with the most recent AIM run where stock status was determined to be overfished and overfishing was currently occurring (Palmer 2008). The most optimistic stock status determination resulted from run 8 (obj. func. = 22.494) estimates F_{2006}/F_{msy} at 0.001 and SSB_{206}/SSB_{msy} at 4.524. The most pessimistic stock status determination resulted from run 1 (obj. func. = 22.103) with estimates of F_{2006}/F_{msy} at 7.730 and SSB_{206}/SSB_{msy} at 0.031. All three formulations of the LOSS model have trouble matching the survey biomass index (Fig. 2). This may be partly explained because the Gulf of Maine haddock stock has been driven in recent history (post-1963) by periodic pulses of strong year classes. Strong year classes occurring at low spawning stock biomass violates the LOSS model's assumption of deterministic recruitment.

Given the inability to determine a "best" model formulation and the wide ranging implications on stock status, the LOSS model is not a good candidate with which to determine biological reference points for Gulf of Maine haddock.

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Tables

Table 1. Total catch (mt) and NEFSC autumn bottom trawl survey biomass (kg/tow) indices for Gulf of Maine haddock from 1963 to 2006. Total catch includes United States and international commercial landings, commercial discards and recreational landings.

Year	Total catch (mt)	NEFSC autumn survey biomass (kg/tow)
1963	4,789	50.697
1964	5,841	18.386
1965	4,624	17.731
1966	5,855	13.103
1967	5,499	16.871
1968	3,557	17.307
1969	2,698	12.721
1970	1,543	7.354
1971	1,316	8.159
1972	955	3.036
1973	607	8.583
1974	874	3.347
1975	1,333	8.616
1976	2,002	8.040
1977	3,357	8.752
1978	5,096	21.658
1979	4,438	15.567
1980	6,544	9.835
1981	6,272	10.874
1982	6,993	4.164
1983	7,656	5.219
1984	4,092	3.893
1985	3,057	6.149
1986	1,852	1.392
1987	849	2.645
1988	433	1.476
1989	292	0.631
1990	440	0.432
1991	435	0.120
1992	331	0.091
1993	223	0.472
1994	217	0.217
1995	457	1.099
1996	360	3.543
1997	1,001	2.424
1998	958	2.917
1999	569	4.910
2000	944	14.032
2001	1,169	11.981
2002	1,167	4.835
2003	1,237	5.359
2004	1,402	7.171
2005	1,717	3.932
2006	1,171	3.945

Table 2. Input vectors for natural mortality (M), weight-at-age (WAA), maturity-at-age (MAA), fleet selectivity and index selectivity.

Age	**M**	**WAA**	**MAA**	**Fleet selectivity**	**Index selectivity**
0	0.2	0.001	0.0	0.01	0.5
2	0.2	0.368	0.2	0.10	1.0
3	0.2	0.699	0.6	0.50	1.0
4	0.2	0.996	0.9	1.00	1.0
5	0.2	1.264	1.0	1.00	1.0
6	0.2	1.504	1.0	1.00	1.0
7	0.2	1.720	1.0	1.00	1.0
8	0.2	1.915	1.0	1.00	1.0
9	0.2	2.089	1.0	1.00	1.0
10	0.2	2.247	1.0	1.00	1.0
11	0.2	2.388	1.0	1.00	1.0
12	0.2	2.515	1.0	1.00	1.0
13	0.2	2.630	1.0	1.00	1.0
14	0.2	2.733	1.0	1.00	1.0
15	0.2	2.825	1.0	1.00	1.0
16	0.2	2.908	1.0	1.00	1.0
17	0.2	2.983	1.0	1.00	1.0
18	0.2	3.050	1.0	1.00	1.0
19	0.2	3.111	1.0	1.00	1.0
20	0.2	3.165	1.0	1.00	1.0

Table 3. Summary of Long-term Observation-error Survey Series (LOSS) model run results with the input scalars, steepness and depletion (S1/S0), varied from 0.25 to 0.95 by 0.1 and 0.1 to 1.0 by 0.1 respectively.

Run	Steepness	S1/S0	Objective function	Sigma	S0	R0	Fmsy	SSBmsy	Fratio	SSBratio
1	0.25	0.1	22.103	1.109	536,893	92,615	0.02	252,882	7.73	0.03
2	0.35	0.1	22.030	1.030	288,106	49,699	0.07	122,226	3.54	0.05
3	0.45	0.1	21.960	0.961	194,742	33,593	0.11	75,175	2.35	0.08
4	0.55	0.1	21.895	0.900	146,260	25,230	0.15	51,524	1.68	0.11
5	0.65	0.1	22.109	1.115	116,260	20,055	0.20	37,276	0.18	0.95
6	0.75	0.1	22.438	1.550	95,358	16,449	0.27	27,581	0.08	3.82
7	0.85	0.1	22.517	1.677	427,613	73,764	0.35	109,454	0.01	3.82
8	0.95	0.1	22.494	1.640	456,217	78,698	0.48	98,917	0.01	4.52
9	0.25	0.2	22.102	1.108	279,966	48,295	0.02	131,867	7.60	0.06
10	0.35	0.2	22.027	1.027	160,772	27,733	0.07	68,206	3.41	0.09
11	0.45	0.2	21.954	0.955	114,918	19,824	0.11	44,361	2.22	0.14
12	0.55	0.2	21.886	0.892	90,750	15,655	0.15	31,969	1.53	0.19
13	0.65	0.2	21.951	0.952	75,797	13,075	0.20	24,303	0.32	0.85
14	0.75	0.2	22.272	1.313	65,575	11,312	0.27	18,967	0.12	2.11
15	0.85	0.2	22.421	1.523	58,008	10,007	0.35	14,848	0.09	2.88
16	0.95	0.2	22.449	1.567	311,912	53,805	0.48	67,629	0.01	4.48
17	0.25	0.3	22.101	1.107	194,278	33,513	0.02	91,507	7.47	0.09
18	0.35	0.3	22.024	1.024	118,560	20,452	0.07	50,298	3.29	0.13
19	0.45	0.3	21.949	0.951	88,789	15,316	0.11	34,275	2.10	0.18
20	0.55	0.3	21.879	0.886	72,860	12,569	0.15	25,667	1.42	0.26
21	0.65	0.3	21.858	0.868	62,904	10,851	0.20	20,169	0.47	0.70
22	0.75	0.3	22.179	1.196	56,140	9,684	0.27	16,238	0.15	2.80
23	0.85	0.3	22.331	1.392	51,133	8,820	0.35	13,088	0.10	2.80
24	0.95	0.3	22.421	1.523	47,210	8,144	0.48	10,236	0.08	3.57
25	0.25	0.4	22.101	1.106	151,497	26,134	0.02	71,357	7.35	0.12
26	0.35	0.4	22.022	1.022	97,575	16,832	0.07	41,395	3.19	0.16
27	0.45	0.4	21.946	0.947	75,942	13,100	0.11	29,315	2.01	0.23
28	0.55	0.4	21.873	0.881	64,224	11,079	0.15	22,624	1.33	0.31
29	0.65	0.4	21.818	0.833	56,833	9,804	0.20	18,222	0.62	0.60
30	0.75	0.4	22.116	1.123	51,869	8,947	0.27	15,003	0.17	2.00
31	0.85	0.4	22.274	1.315	48,213	8,317	0.35	12,341	0.11	2.77
32	0.95	0.4	22.367	1.444	45,404	7,832	0.48	9,845	0.08	3.53
33	0.25	0.5	22.100	1.105	125,846	21,709	0.02	59,275	7.24	0.14
34	0.35	0.5	22.020	1.020	85,035	14,669	0.07	36,075	3.09	0.19
35	0.45	0.5	21.943	0.944	68,324	11,786	0.11	26,375	1.93	0.26
36	0.55	0.5	21.869	0.878	59,160	10,205	0.15	20,841	1.27	0.35
37	0.65	0.5	21.805	0.823	53,330	9,199	0.20	17,099	0.69	0.58
38	0.75	0.5	22.072	1.074	49,448	8,530	0.27	14,303	0.18	2.74
39	0.85	0.5	22.234	1.264	46,590	8,037	0.35	11,925	0.12	2.74
40	0.95	0.5	22.331	1.393	44,398	7,659	0.48	9,626	0.08	3.51
41	0.25	0.6	22.099	1.104	108,738	18,758	0.02	51,217	7.13	0.17
42	0.35	0.6	22.018	1.018	76,691	13,229	0.07	32,535	3.01	0.22
43	0.45	0.6	21.940	0.942	63,268	10,914	0.11	24,423	1.86	0.29
44	0.55	0.6	21.867	0.875	55,810	9,627	0.15	19,661	1.22	0.39
45	0.65	0.6	21.799	0.818	51,018	8,801	0.20	16,358	0.74	0.57
46	0.75	0.6	22.039	1.039	47,850	8,254	0.27	13,840	0.19	1.94
47	0.85	0.6	22.205	1.227	45,508	7,850	0.35	11,649	0.12	2.72
48	0.95	0.6	22.304	1.356	43,700	7,538	0.48	9,475	0.08	3.50
49	0.25	0.7	22.099	1.104	96,540	16,653	0.02	45,472	7.02	0.19
50	0.35	0.7	22.017	1.017	70,742	12,203	0.07	30,011	2.93	0.24
51	0.45	0.7	21.939	0.941	59,651	10,290	0.11	23,027	1.81	0.32
52	0.55	0.7	21.865	0.874	53,408	9,213	0.15	18,814	1.18	0.42
53	0.65	0.7	21.796	0.816	49,353	8,513	0.20	15,824	0.77	0.57
54	0.75	0.7	22.013	1.013	46,687	8,054	0.27	13,504	0.19	2.71
55	0.85	0.7	22.181	1.198	44,706	7,712	0.35	11,443	0.12	2.71
56	0.95	0.7	22.283	1.327	43,162	7,446	0.48	9,358	0.08	3.49
57	0.25	0.8	22.098	1.103	87,404	15,077	0.02	41,168	6.92	0.21
58	0.35	0.8	22.016	1.016	66,268	11,431	0.07	28,114	2.87	0.27
59	0.45	0.8	21.938	0.940	56,921	9,819	0.11	21,973	1.76	0.34
60	0.55	0.8	21.864	0.873	51,582	8,898	0.15	18,171	1.14	0.44
61	0.65	0.8	21.796	0.815	48,079	8,294	0.20	15,416	0.74	0.60
62	0.75	0.8	21.992	0.992	45,782	7,897	0.27	13,242	0.20	1.90
63	0.85	0.8	22.162	1.175	44,068	7,602	0.35	11,280	0.13	2.70
64	0.95	0.8	22.265	1.303	42,720	7,369	0.48	9,263	0.09	3.48
65	0.25	0.9	22.097	1.102	80,301	13,852	0.02	37,823	6.82	0.23
66	0.35	0.9	22.015	1.015	62,782	10,830	0.07	26,635	2.80	0.29
67	0.45	0.9	21.937	0.939	54,775	9,449	0.11	21,144	1.71	0.36
68	0.55	0.9	21.864	0.872	50,134	8,648	0.15	17,661	1.12	0.47
69	0.65	0.9	21.796	0.815	47,058	8,117	0.20	15,088	0.73	0.63
70	0.75	0.9	21.974	0.975	45,045	7,770	0.27	13,029	0.20	2.69
71	0.85	0.9	22.145	1.156	43,539	7,511	0.35	11,145	0.13	2.69
72	0.95	0.9	22.250	1.284	42,343	7,304	0.48	9,181	0.09	3.47
73	0.25	1.0	22.097	1.102	74,622	12,873	0.02	35,148	6.73	0.25
74	0.35	1.0	22.014	1.014	59,981	10,347	0.07	25,446	2.75	0.30
75	0.45	1.0	21.937	0.938	53,034	9,149	0.11	20,472	1.68	0.38
76	0.55	1.0	21.864	0.872	48,946	8,443	0.15	17,243	1.09	0.49
77	0.65	1.0	21.796	0.816	46,211	7,971	0.20	14,817	0.71	0.65
78	0.75	1.0	21.960	0.961	44,425	7,663	0.27	12,849	0.21	1.87
79	0.85	1.0	22.131	1.140	43,086	7,432	0.35	11,029	0.13	2.68
80	0.95	1.0	22.237	1.267	42,012	7,247	0.48	9,109	0.09	3.46

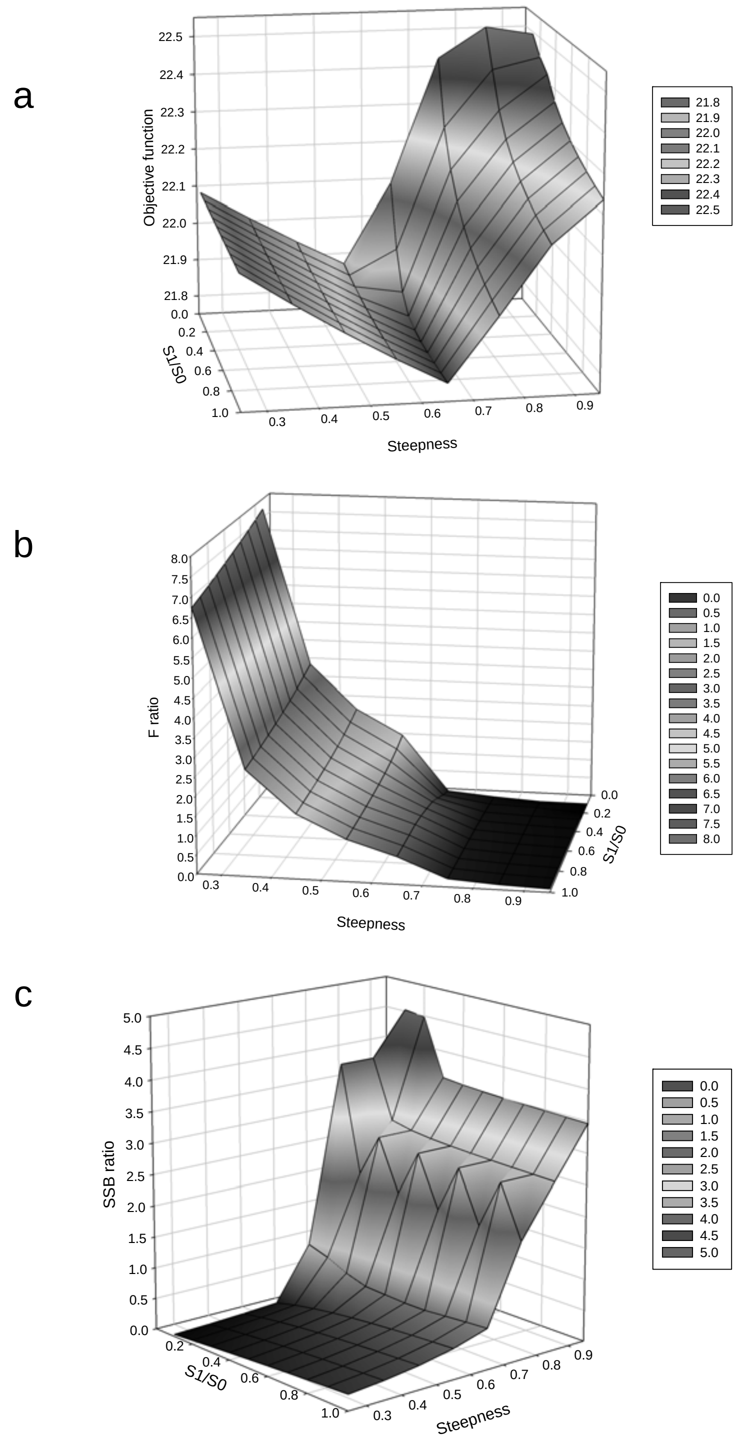

Fig. 1. Surface plots of the response of the (a) objective function, (b) F-ratio, (c) SSB-ratio to variations of the steepness and depletion (S1/S0) input variables in runs of the Long-term Observation-error Survey Series (LOSS) model on the Gulf of Maine haddock stock.

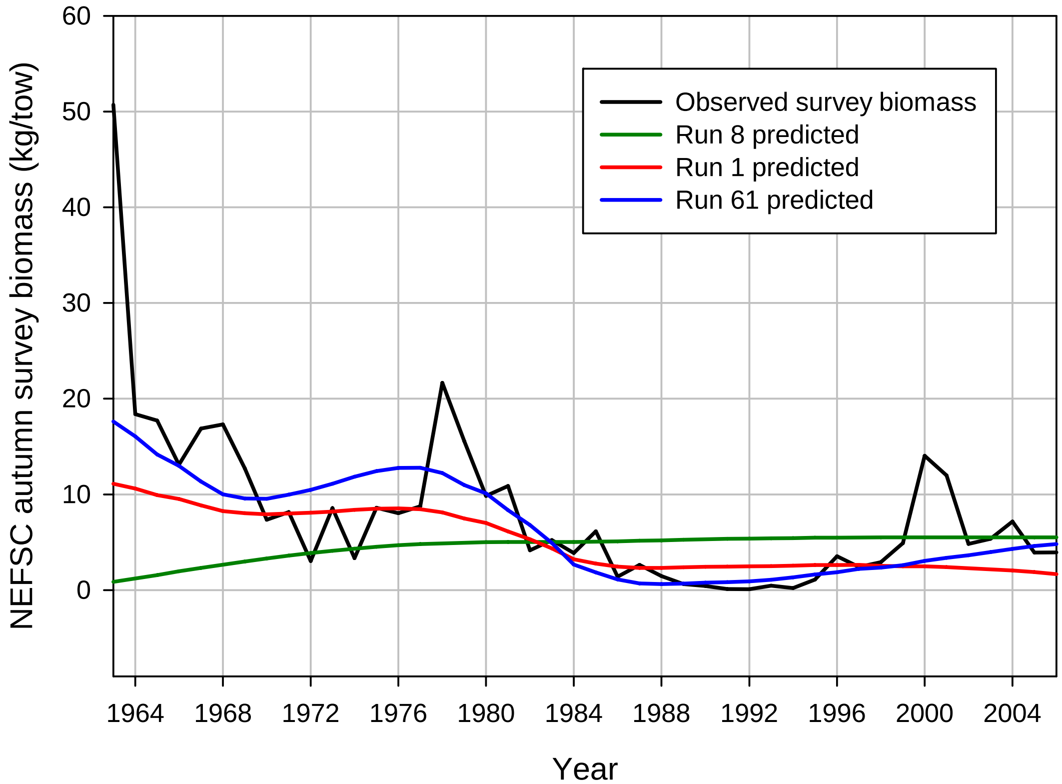

Fig. 2. Observed and predicted Gulf of Maine haddock NEFSC autumn survey biomass indices for three runs of the Long-term Observation-error Survey Series (LOSS) model. The runs shown represent the model run with the lowest objective function (run 61), most optimistic stock status (run 8), and pessimistic stock status (run 1).

Appendix A. The Long-term Observation-error Survey Series (LOSS) model

Population Dynamics

The LOSS model is a simple age-structured production model with a deterministic stock recruitment relationship. Population abundance at age is defined by

$$N_{y+1,a} = R_{y+1} \qquad \text{for } a=1$$

$$N_{y+1,a} = N_{y,a-1}e^{-(M_{a-1}+F_{y,a-1})} \qquad \text{for } 1<a<A$$

$$N_{y+1,a} = N_{y,a-1}e^{-(M_{a-1}+F_{y,a-1})} + N_{y,a}e^{-(M_{a-1}+F_{y,a})} \qquad \text{for } a=A$$

where:

$N_{y,a}$ is the population abundance of age a at the start of year y,
R_y is the number of age 1 at the start of year y,
M_a is the instantaneous natural mortality rate of age a,
$F_{y,a}$ is the instantaneous fishing mortality rate of age a during year y,
A is the accumulator age (aka plus group).

Fishing mortality is assumed to be separable into year and age components such that

$$F_{y,a} = F_y S_a$$

where:

F_y is the fishing mortality multiplier for year y,
S_a is the fishery selectivity for age a, assumed constant over all years.

Recruitment is predicted from a Beverton-Holt stock-recruitment relationship

$$R_{y+1} = \frac{\alpha\, SSB_y}{\beta + SSB_y}$$

where:

SSB_y is the spawning stock biomass in year y computed as

$$SSB_y = \sum_{a=1}^{A} W_a m_a N_{y,a} e^{-p(M_a+F_{y,a})}$$

where:

W_a is the individual fish weight at age a, assumed constant over all years,
m_a is the proportion of fish age a which are mature,
p is the proportion of mortality occurring during the year prior to spawning.

α is a parameter of the stock recruitment relationship defined by

$$\alpha = \frac{4\,\tau\, R_0}{5\tau - 1}$$

β is a parameter of the stock recruitment relationship defined by

$$\beta = \frac{SSB_0(1-\tau)}{5\tau - 1}$$

where:

τ is the steepness of the stock-recruitment relationship,
R_0 is the unfished recruitment, derived as SSB_0/SPR_0,
SSB_0 is the unfished spawning stock biomass,
SPR_0 is the unfished spawning stock biomass per recruit.

The user inputs steepness, while the unfished spawning stock biomass is a parameter in the model. These two values, in combination with the biological and fishery inputs, determine the stock recruitment relationship.

Catch

Predicted catch at age in the model is derived from the Baranov catch equation

$$C_{y,a} = N_{y,a} \frac{F_{y,a}}{M_a + F_{y,a}} (1 - e^{-(M_a + F_{y,a})})$$

and the predicted annual catches in weight (yield) are

$$Y_y = \sum_{a=1}^{A} C_{y,a} W_a \ .$$

Initial Population

The staring population abundance at age is determined by an input parameter called depletion which is the ratio of spawning stock biomass in the first year of the model to the unfished spawning stock biomass. The program uses a bisection algorithm to solve for the fishing mortality rate multiplier that produces the input depletion given the input conditions of fishery selectivity, natural mortality, weight at age, and maturity at age.

Indices

The user supplies a time series of observed index values (O_y), missing values are allowed. The program computes predicted indices as

$$I_y = q\,B_y$$

where:

q is the scaler relating population biomass to the index, determined by

$$q = \exp\left(\frac{1}{n} \sum_{y=1}^{n} \left(\ln(O_y) - \ln(B_y) \right) \right)$$

B_y is the population biomass in year y, determined by

$$B_y = \sum_{a=1}^{A} N_{y,a} W_a$$

and n is the number of non-missing index observations.

Objective Function

The LOSS model is programmed in ADMB (tpl source code available from the authors) and uses a negative log likelihood as the objective function to be minimized. The model is fit to a tuning index supplied by the user assuming a lognormal error structure and ignores constants as

$$-\ln L_i = \ln(\sigma) + 0.5 \sum_{y=1}^{n} \frac{\left(\ln(O_y) - \ln(I_y) \right)^2}{\sigma^2}$$

where:

σ is the standard deviation in the fit between observed and predicted indices

$$\sigma = \sqrt{\frac{1}{n}\sum_{y=1}^{n}\left(\ln(Oy) - \ln(Iy)\right)^2}$$

Thus, the likelihood equation for the index fit simplifies to
$-\ln L_i = \ln(\sigma) + 0.5n$.

The second component of the objective function which is minimized is difference between the total catch in weight each year observed (X_y) and predicted (Y_y)
$-\ln L_c = 0.5\sum_{y=1}^{nyears}\left(X_y - Y_y\right)^2$.
The program usually has no problem fitting the observed and predicted catch so that this term is usually zero.

The final component of the objective function is a penalty for the fishing rate multiplier going above 5. This is essentially a penalty that prevents the biomass from becoming unbelievably small but still meeting the catch
$-\ln L_p = 10000(F_y - 5)^2$ for $F_y > 5$.

The objective function minimized by ADMB is the sum of the three negative likelihoods ($-lnL_i$ + $-lnL_c$ + $-lnL_p$).